DTU Library

TOPFARM - topology optimization as seen from an investor's perspective

Larsen, Gunner Chr.

Publication date:
2013

TOPFARM - topology optimization as seen from an investors perspective

G.C. Larsen et al.

DTU Wind Energy
Department of Wind Energy

Outline

- Introduction
- Single *objective* WF optimization
  - One parameter optimization … e.g. power
  - Multi-parameter optimization … economics
- TOPFARM
  - Vision and philosophy
  - Basic elements
  - WF flow field module
  - WT aeroelastic module
  - Cost model module
  - Synthesis – the objective function
  - Numeric's and example applications
  - References

Introduction (1)

- *Motivation*: The majority of wind turbines are nowadays erected in WF’s due to practical and economic reasons associated with e.g.
  - Public acceptance
  - Land ownership and public regulation
  - Savings on infrastructure and maintenance

Introduction (2)

- *Definition of problem*: Given the ambient wind climate (measured or modeled)
  - Mean wind distribution ... conditioned on wind direction (deterministic)
  - Roughness/shear ... conditioned on wind direction (deterministic)
  - Turbulence parameter distributions ... conditioned on wind direction (stochastic)
  - Wind direction distribution

  determine the ”optimal” WF layout/topology ... possible including (optimal) WT and WF control

Introduction (3)

- *Challenges*:
  - Computational speed, ... , computational speed
  - Description of the in-stationary WF flow field
  - Reliable cost models ... including determination of an optimal grid layout in each iterative step of the "overall" WF optimization
  - Efficient and robust optimization strategy ensuring convergence to a global optimum ... and potentially including sensitivity considerations
  - WT and WF control integrated in the optimization

Single objective WF optimization

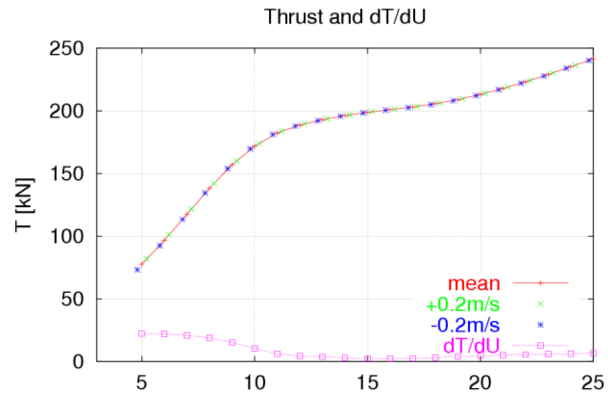
- Examples of potential approaches
  - One-parameter approach: Optimizing the *power output* … and ensuring that that the loading of the individual turbines is beneath their design limit
  - Multi-parameter approach: Optimizing WF topology from a “holistic” *economical* point of view … throughout the life time of the WF
    - The Pareto frontier collapsed to a “point” in design space … by suitable formulation of the objective function (TOPFARM)

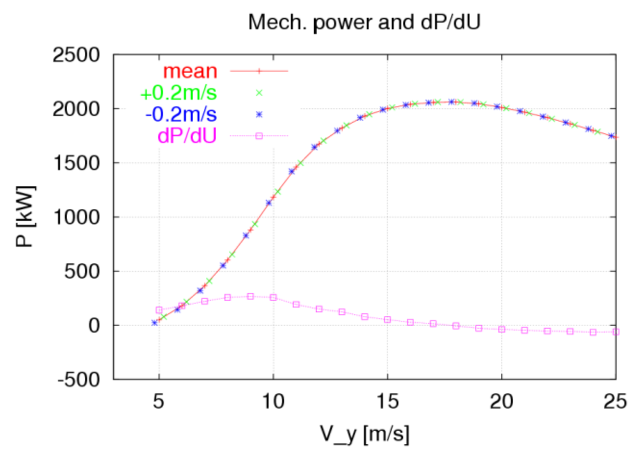
One parameter optimization – input (1)

- Mean wind distribution ... conditioned on wind direction (deterministic)
- Roughness/shear ... conditioned on wind direction (deterministic)
- Turbulence parameter distributions ... conditioned on wind direction (stochastic)
- Wind direction distribution

One parameter optimization – input (2)

- *Wind Turbines* (WT) strongly simplified and basically represented by characteristics as:
    - Thrust curve ("flow resistance")
    - Power curve (production)





One parameter optimization – WF flow field

- Typically modelled using *stationary* approaches, such as e.g.
  - The N.O. Jensen model (simple top hat model based on momentum balance)
  - Parabolised CFD models with an eddy viscosity closure (UPM model (ECN WindPRO), Ainsley model (GH Windfarmer), ...)
  - Linearized RANS model (FUGA) based on a first order perturbation approach. Numerical diffusion omitted! (mixed spectral formulation). Extremely fast! ... appr. 1 mill faster than conventional RANS

One parameter optimization – objective fct.

- Relatively simple ... because all elements have the *same unit*
- No cost models are consequently required!
- Objective function ... to be optimized:

$$P_{tot} = \sum_{life\ time} \sum_{pdf\ \theta} \sum_{pdf\ U} \sum_{i=1}^{N} P(x_i, y_i)$$

Multi-parameter optimization – input

- In a “true” rational *economical optimization* of the WF layout, the goal is to determine the *optimal balance* between capital costs, operation and maintenance (O&M) costs, fatigue lifetime consumption and power production output ... possibly under certain specified constraints (e.g. area, distance between turbines, ...
- Same input as used for optimizing power production ... supplemented by
    - Wind turbine information sufficiently detailed for setting up aeroelastic model(s) of the turbines in question
    - Cost model input (including interest rates)

Multi-parameter optimization – WF flow field

- Stationary flow fields and rudimentary WT models may suffice for optimizing wind power production … but is clearly *not* sufficient for achieving the overall economical WF optimum
    - *In-stationary* characteristics of the WF flow field have to be considered to enable prediction of reliable WT dynamic loading … which is essential for fatigue load estimation, cost of O&M, … This presents a considerable complication!

Multi-parameter optimization – modeling

- Compared to single-parameter optimization, additional modeling is required not only for the WF flow field:
  - Detailed WT modeling (i.e. *aeroelastic modeling* with WT control included) is needed to obtain main component structural response in sufficient detail and of sufficient accuracy
  - Cost models are needed to aggregate different types of quantities into an objective function

TOPFARM – vision and philosophy

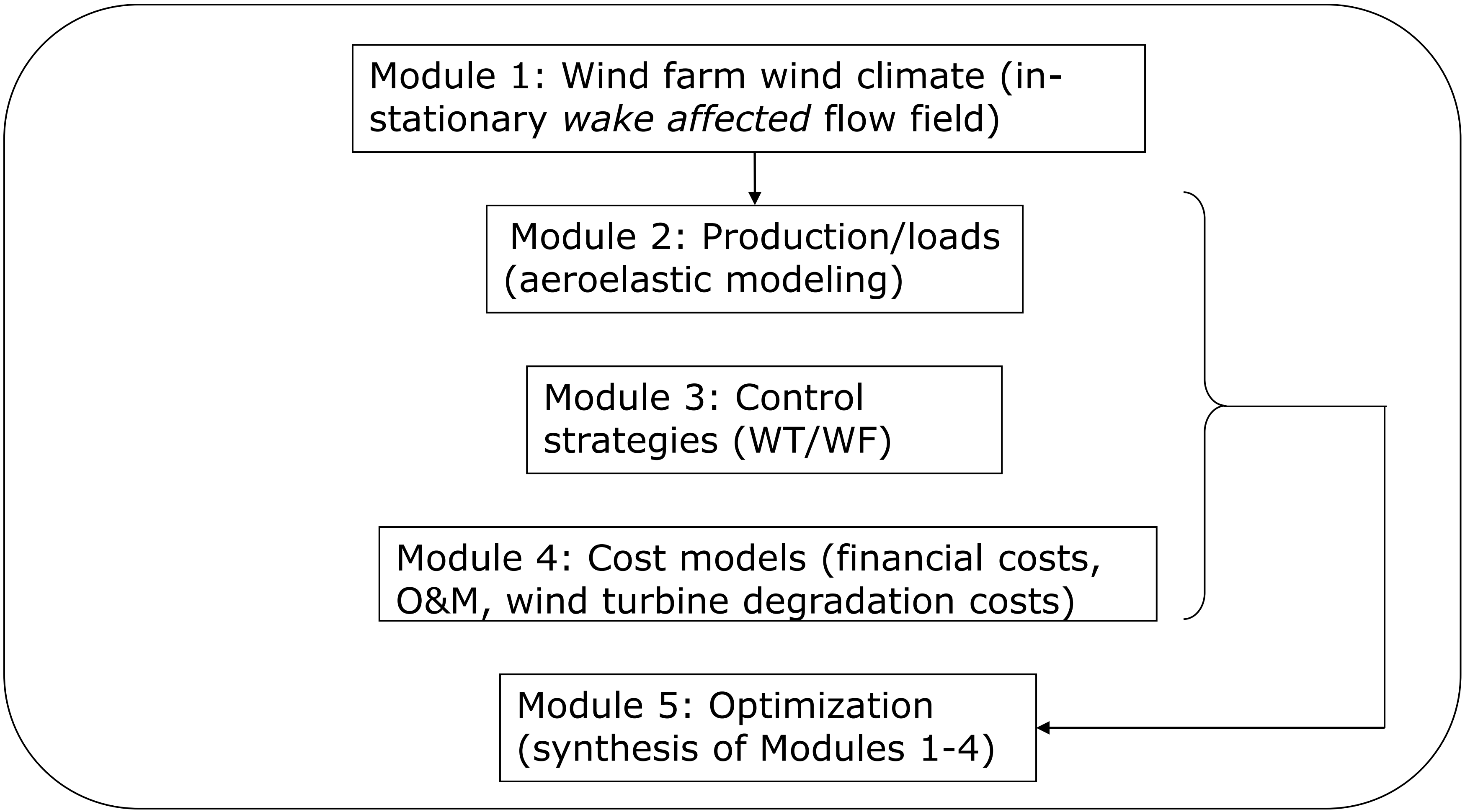
- Vision: A "complete" wind farm topology optimization, as seen from an investors perspective, taking into account:
  - *Loading*- and *production* aspects in a realistic and coherent framework
  - Financial costs (foundation, grid infrastructure, ...)

  … and and subjected to various constraints (area, spacing , ...)
- Philosophy: The optimal wind farm layout reflects the *optimal economical performance* as seen over the lifetime of the wind farm

TOPFARM – key factors

- The main parameters influencing/dictating WF economics include the following:
  - Investment costs - including auxiliary costs for foundation, grid connection, civil engineering infrastructure, ...
  - Operation and maintenance costs (O&M)
  - Electricity production
  - Turbine loading (lifetime of WT components)
  - Discounting rate

TOPFARM – basic elements

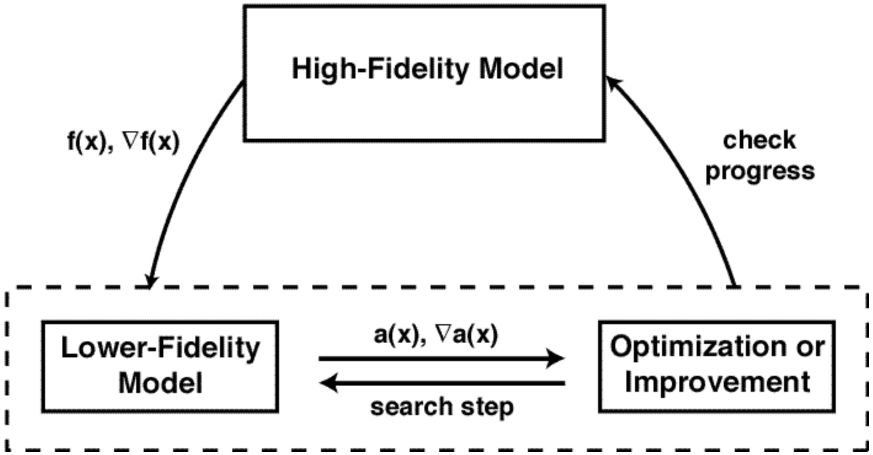


TOPFARM – WF flow field module (1)

- WF wind climate deviates significantly from ambient wind climate:
  - Wind resource (decreased)
  - Turbulence modified
    - Turbulence intensity increased
    - Turbulence structure modified … incl. intermittency caused by dynamic WF turbine interaction though wakes

TOPFARM – WF flow field module (2)

- The TOPFARM multi-fidelity optimization approach requires a hierarchy of models



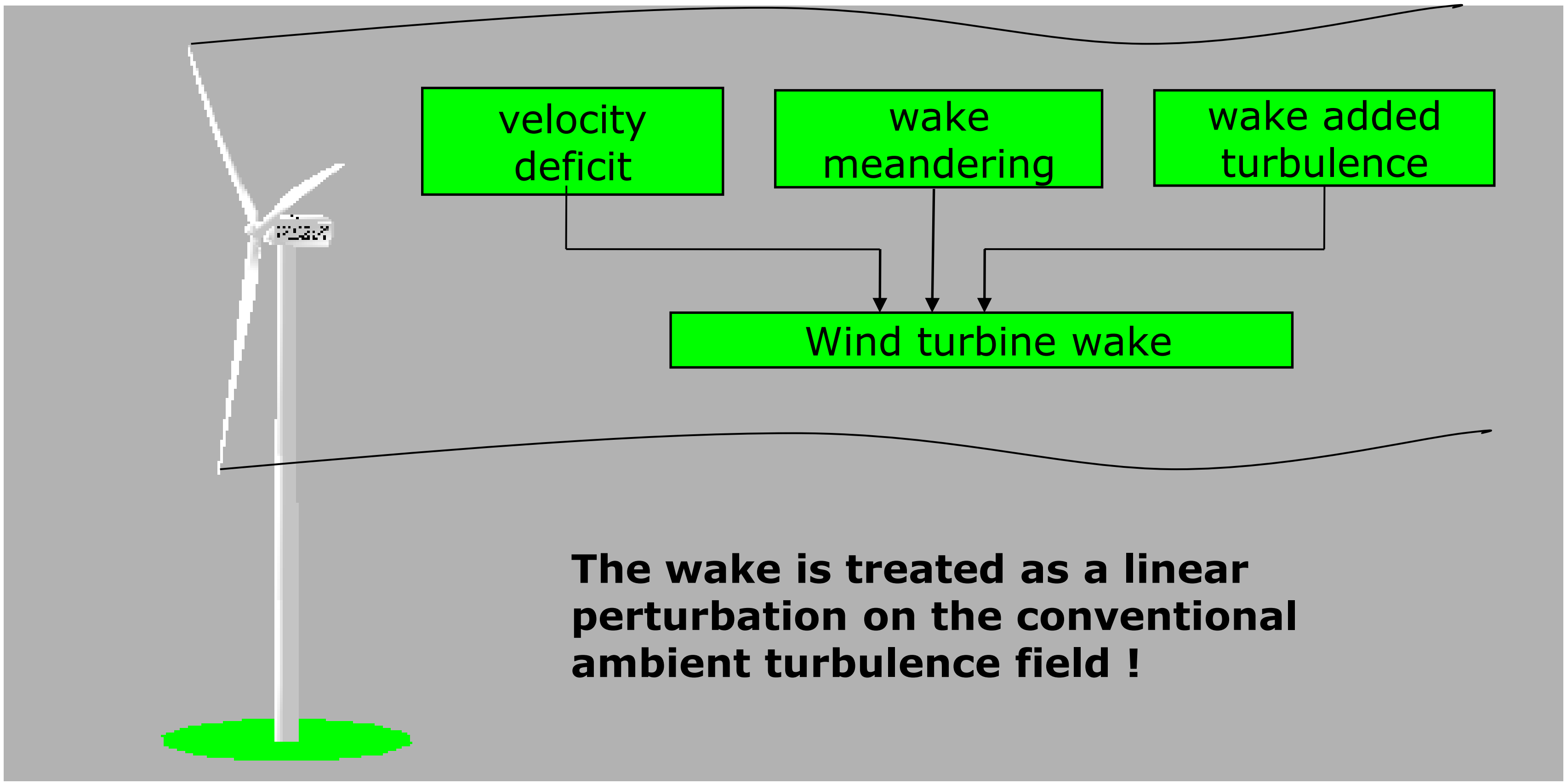
1. Stationary wake (analytical model) + Power curve
2. “Poor man’s LES”; i.e. DWM (Database – generic production/load cases + interpolation)
3. DWM (Simulation)

TOPFARM – WF flow field module (3)

- The requested *in-stationary* flow field modeling is based on the DWM approach
- The core of this model is a *split in scales* in the wake flow field, with
  - large turbulent scales being responsible for stochastic *wake meandering*, and
  - small turbulent scales being responsible for wake *attenuation* and *expansion* in the meandering frame of reference as caused by turbulent mixing
- The wake deficit is thus basically treated as a *passive tracer* in the large scale turbulent field – conveniently defined by the cut off frequency f_c $=U/2D$

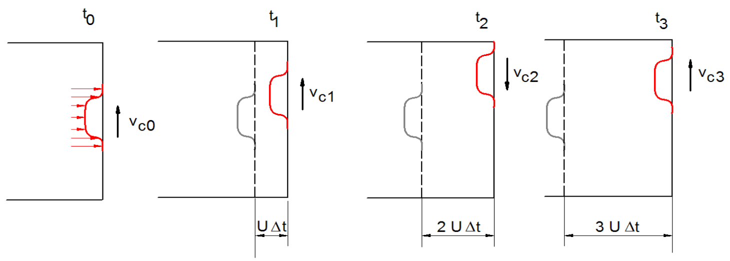
TOPFARM – WF flow field module (4)

- Basic DWM elements:



TOPFARM – WF flow field module (5)

- A word on wake meandering:
  - *Longitudinal transportation* (i.e. transportation in the mean wind direction): *Taylor advection*
  - *In plane (transversal/vertical) transportation:* A 3D turbulence wind field is generated that, after suitable low-pass filtering, is used as "transport media" for the wake



  - A sequence of *"deficit-releases"* is considered - each *deficit* is modelled according to the (U+u) wind speed at the instant of release

TOPFARM – WF flow field module (6)

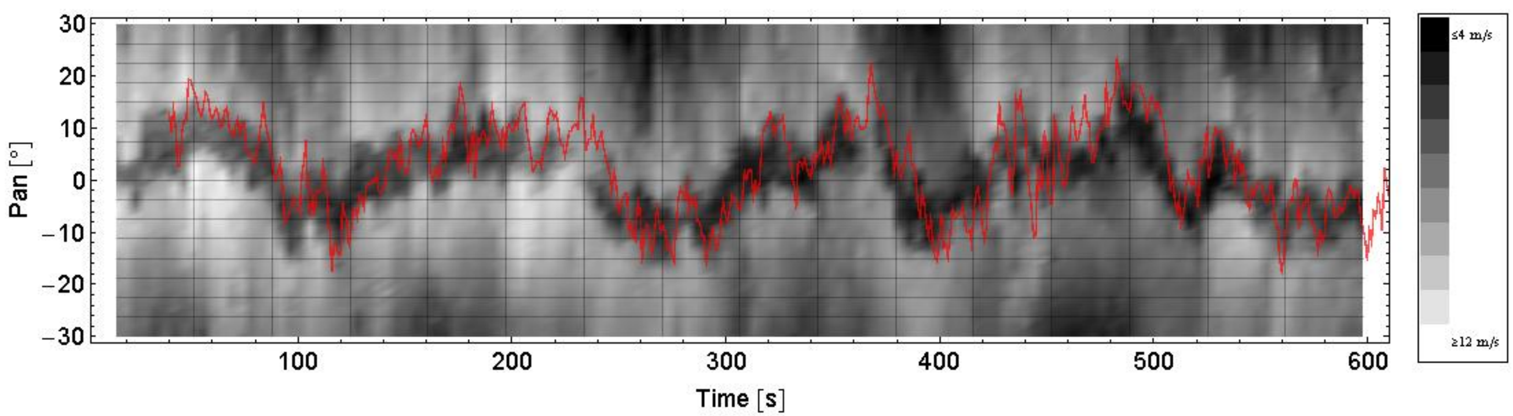
- DWM – the CFD LES analogy:
  - LES *large scale* part dictated by NS - “poor man’s LES” *large scale* dictated by Mann spectral tensor ... which is consistent with NS
  - LES *small scale* part determined by a sub-grid scale turbulence closure model - “poor man’s LES” *small scale* part modelled using a turbulence closure based on the eddy viscosity concept

TOPFARM – WF flow field module (7)

- DWM – validation (1):

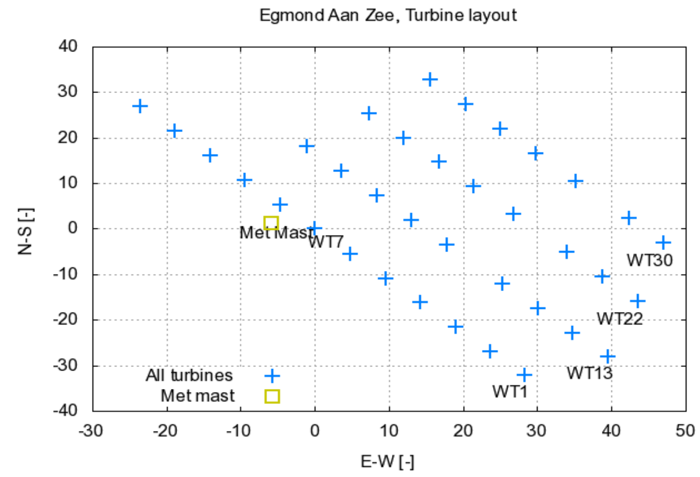
Date 2005–11–15 Time 21:20 Number of Scans 78501

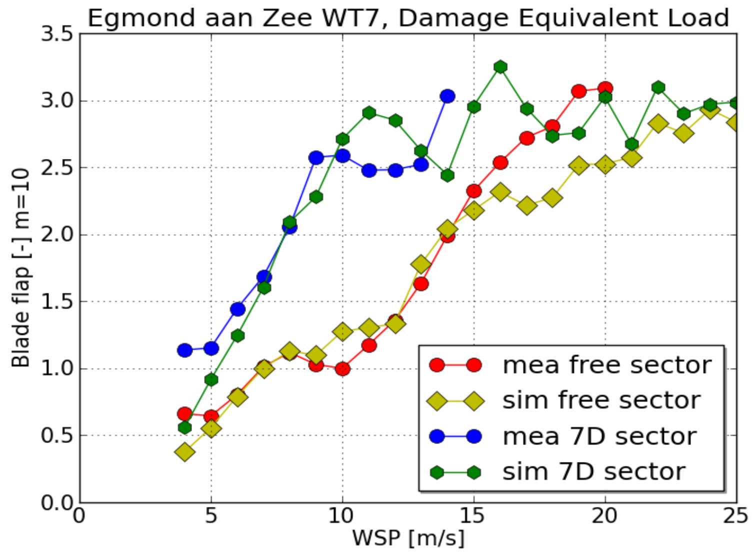
LiDAR				Turbine				Met.Mast							
WS [m/s]				Yaw [°]				WS [m/s]				WD [°]			
Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev
7.76	3.07	13.10	1.56	279.0	258.0	296.0	5.6	8.74	5.43	12.40	1.37	277.0	265.0	289.0	6.0

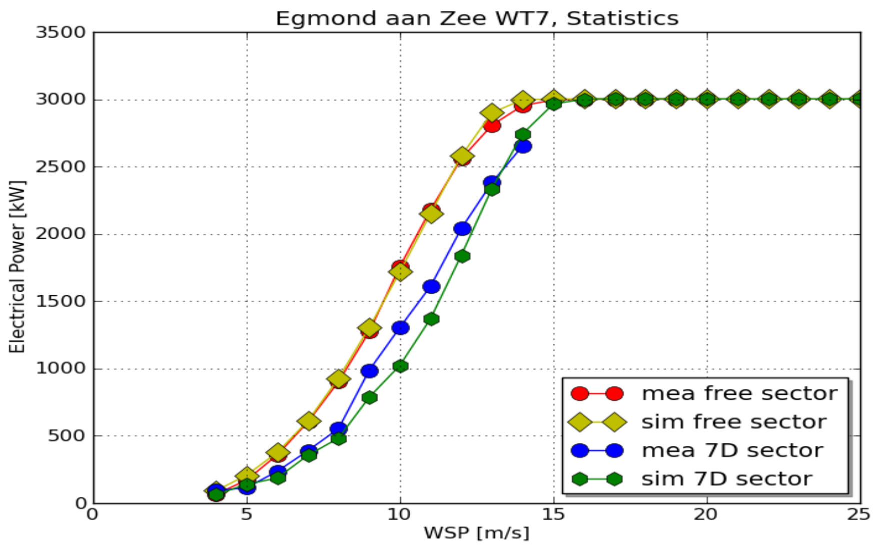


TOPFARM – WF flow field module (8)

- DWM – validation (2):

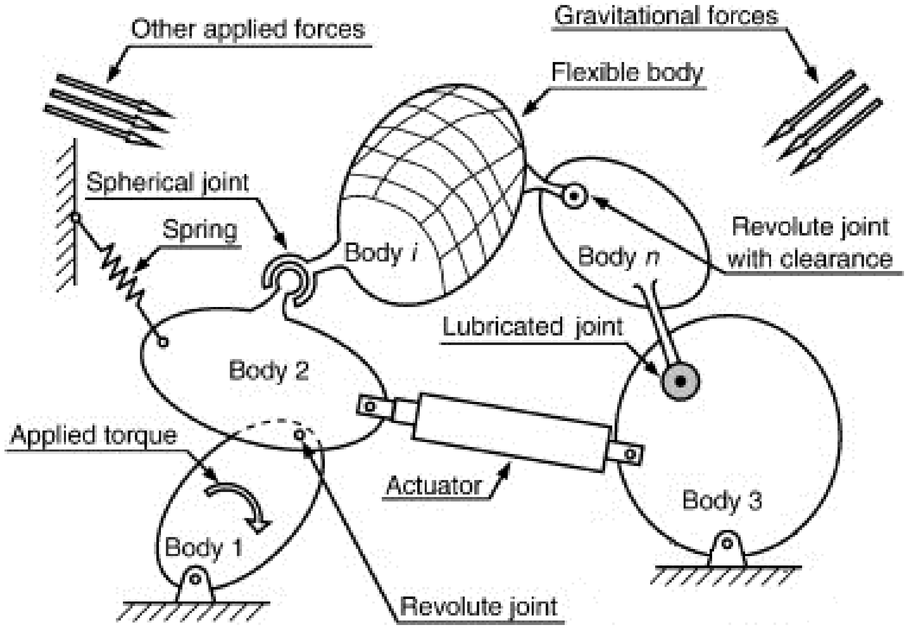


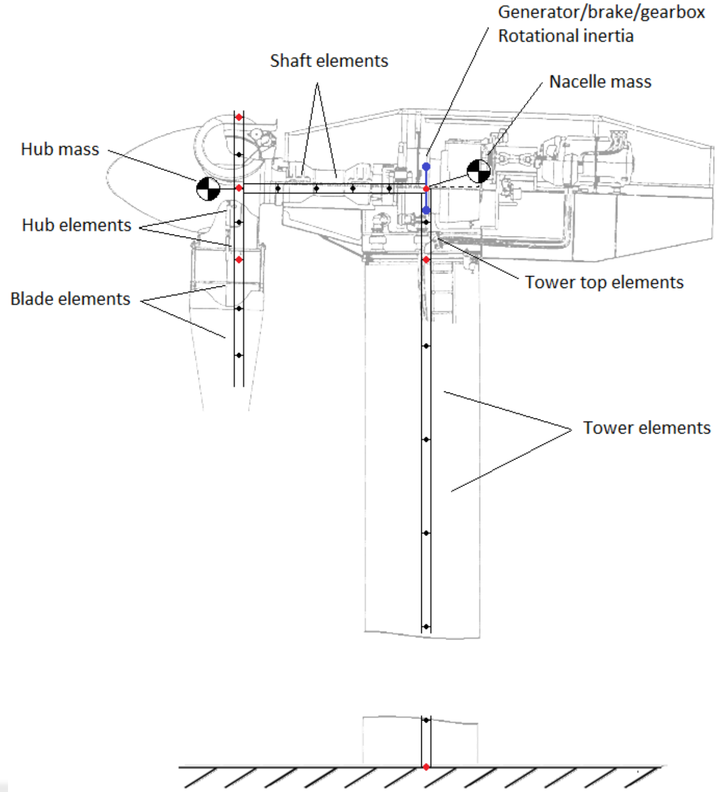




TOPFARM – WT aeroelastic module (1)

- HAWC2:
  - Non-linear FE model based on a multi-body formulation (floating frame of reference)





TOPFARM – WT aeroelastic module (2)

- HAWC2:
  - Aerodynamics based on Blade Element Momentum algorithm and profile look-up tables ... which in turn “delivers” the boundary conditions for the quasi-steady wake deficit simulation in the DWM model
  - WT generator model included
  - WT control algorithms included
  - Output is power and forces/moments in arbitrary selected cross sections

TOPFARM – cost model module (1)

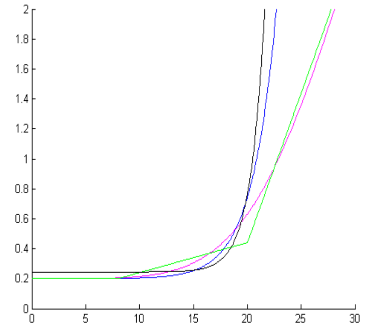
- Basic simplifying approach:
  - Only costs that depend on wind farm topology and control – variable costs – are of relevance in a topology optimization context ... and therefore included
  - Fixed costs may be included in the objective function. However, as seeking the stationary points for this functional involves gradient behaviour only, the fixed costs will not influence the global optimum of the objective function

TOPFARM – cost model module (2)

- Examples of cost models ... required to transform the (physical) quantity in question into an economical value for the OF synthesis:
  - Financial costs
    - Foundation costs
    - Grid infrastructure costs
    - Civil engineering costs
  - Operational costs
    - Turbine degradation (fatigue loading/lifetime)
    - Operation and maintenance costs (O&M)
  - Electricity production/wind resources

TOPFARM – cost model module (3)

- Foundation costs (CF):
  - Foundation costs are variable costs because of the dependence on soil conditions and/or the water depth at the location of each individual turbine
  - Simple offshore foundation cost model:
    - 20 % of turbine price … at 8m water depth
    - For depths above 8m an additional cost of 2% pr. meter … depths above 20 meters very expensive (20% pr. meter)
    - Fast … and easy to refine
    - Different models investigated

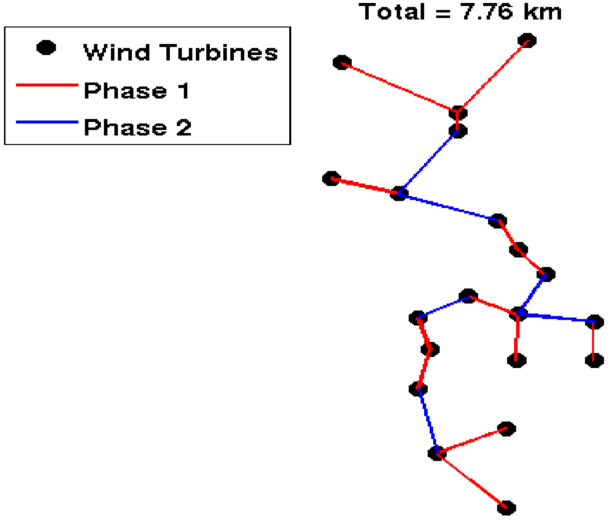


TOPFARM – cost model module (4)

- Grid costs (CF):
  - Presumes a constant price on cabling pr. running meter (including cost of cables, trenching and laying of these)
  - For each topology iteration step, the grid cost is defined as associated with the "shortest possible" connection between all turbines
  - "Idealized" cables able to carry all electricity produced by WTs connected to them

TOPFARM – cost model module (5)

- Grid costs (CF):
  - Approach:
    - Phase 1: Each turbine is connected to its closest neighbour
    - Phase 2: resulting sub-clusters are successively interconnected through their closest turbines



TOPFARM – cost model module (6)

- Cost of WT degradation (CD):
  - Only fatigue driven degradation considered
  - Fatigue damage estimated using Palmgren-Miner linear damage accumulation
  - Based on writing off the investment of the turbines ... specified on main turbine components (S) (i.e. tower, blades, main axis, gear box, generator)

TOPFARM – cost model module (7)

- Cost of WT degradation (CD):
  - The writing off is presumed *proportional* to the *accumulated equivalent moments, L* (or accumulated equivalent stresses) in design critical "hot spots" on the respective components
  - Thus (D_S linear with accumulated fatigue loading)

$$CD = \sum_{N_T} \sum_{S} P_S D_S \;, \qquad D_S = \frac{L_{Sa}}{L_{Sd}} \;,$$

TOPFARM – cost model module (8)

- Cost of O&M (CM):
  - Maintenance Costs are based on the probability of occurrence of a fatigue driven component failure … multiplied by the component replacement cost (incl. loss of production)
  - DS assumed determined with only insignificant uncertainty
  - Material fatigue resistance assumed Log-Normal distributed … significant scatter on Wohler curves

$$CM_S = N_R \times P_{S_r} F\left(D_S; \mu_{S,(R+1)}, \sigma_{S,(R+1)}\right) + P_{S_r} \sum_{j=1}^{R} F\left(D_S; \mu_{S,j}, \sigma_{S,j}\right),$$

TOPFARM – objective function (1)

- Objective function (OF):
  - The objective function represents the synthesis of all modules into an optimization problem
  - OF is formulated as a financial balance expressing the difference between
    - The wind farm *income* (power production (WP)) and
    - The wind farm *expenses;* i.e.
      - O&M expenses (CM)
      - Cost of turbine fatigue load degradation (CD)
      - Financial expenses (C)

TOPFARM – objective function (2)

- Objective function (OF) ... an example:
  - The value of the wind farm power production over the wind farm lifetime, WP, refers to year Zero
  - All operating costs (in this example CD and CM) refer to year Zero … with the implicit assumption that the development of these expenses over time follows the inflation rate … and that the inflation rate is the natural choice for the discounting factor transforming these running costs to *net present value*

$$FB = WP_n - C\left(1+\left(\frac{r_{c1}-r_i}{N_L}\right)\right)^{XN_L} \quad , \quad WP_n = WP - CD - CM \quad ,$$

  - C denotes the financial expenses (here including grid costs (CG) and foundation costs (CF))

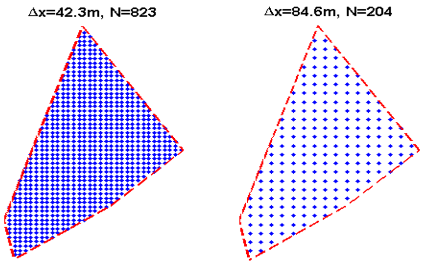
TOPFARM – numeric's (1)

- Optimization approach … some tricks to reduce computational time:
  - Structured grids (i.e. reduction of the design space)
  - Multi-fidelity optimization approach based on 2 (3) levels of sophistication

Fidelity Level	1st	2nd	3rd
Electricity sales	Stationary wake + Power curve	HAWC2-DWM Database	HAWC2-DWM Simulations
Fatigue costs	No	HAWC2-DWM Database	HAWC2-DWM Simulations
Foundation costs	Yes	Yes	Yes
Electrical Grid costs	Yes	Yes	Yes
Optimization algorithm	SGA	SLP or SGA+SLP	SLP
Domain discretization	Coarse	Fine	Fine
Wind speed and direction bin size	Coarse	Fine	Fine

TOPFARM – numeric's (2)

- Selected optimization algorithm is a mix of 2 algorithms:
  - Genetic Algorithm (SGA) with key characteristics
    - Structured grid – coarse resolutic
    - Slow (many iterations necessary)
    - Global optimum … usually
  - Gradient Based Search (SLP) with characteristics
    - Unstructured grid (good for refinements)
    - Fast (few iterations for converging)
    - Local minimum
  - SGA+SLP is a good combination for searching a refined global optimum

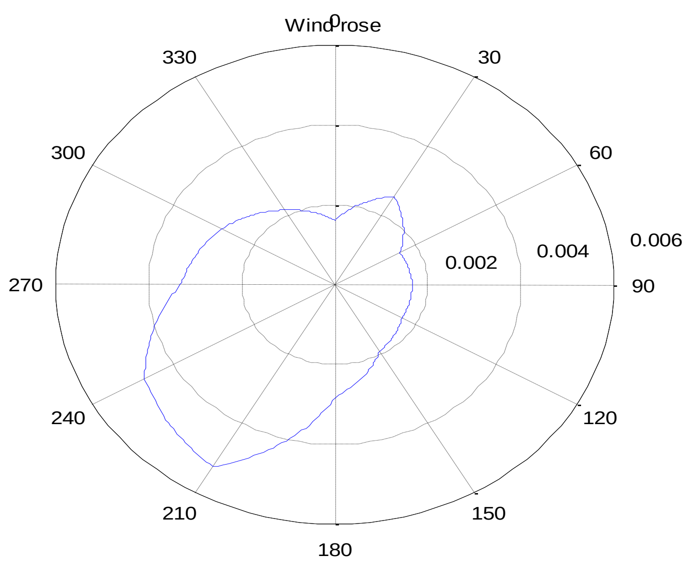


TOPFARM – numeric's (3)

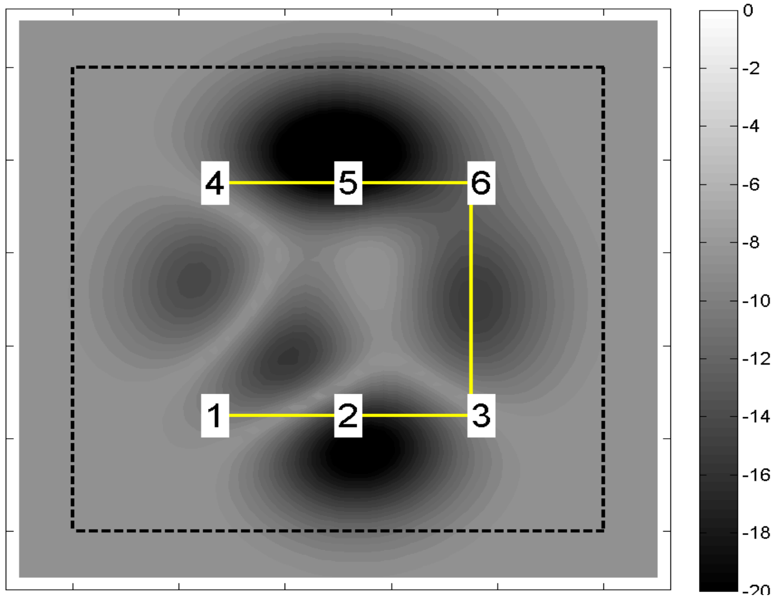
- A word on constraints:
  - Domain boundaries (i.e. limit the domain spanned by the design variables)
    - Explicit limits: e.g. individual wind turbine coordinates within a predefined domain
    - Integral values: resulting from calculation in addition to the cost function (e.g. maximum allowable turbine loads, minimum distance between turbines, power quality – small sensitivity on wind direction changes)

TOPFARM – example applications (1)

- Generic offshore wind farm … used for a sanity check:
  - 6 × 5MW offshore wind turbines
  - Water depths between 4m and 20m



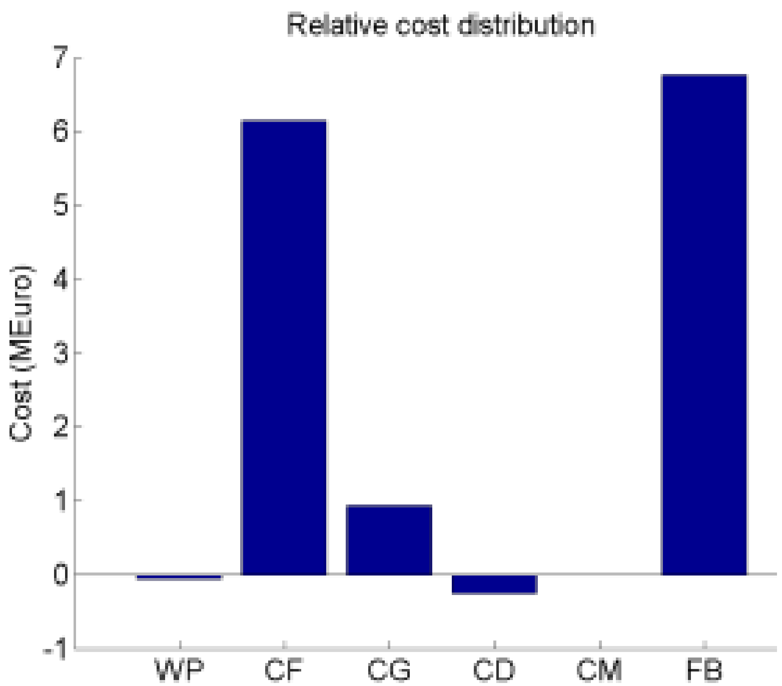
Wind direction probability density distribution

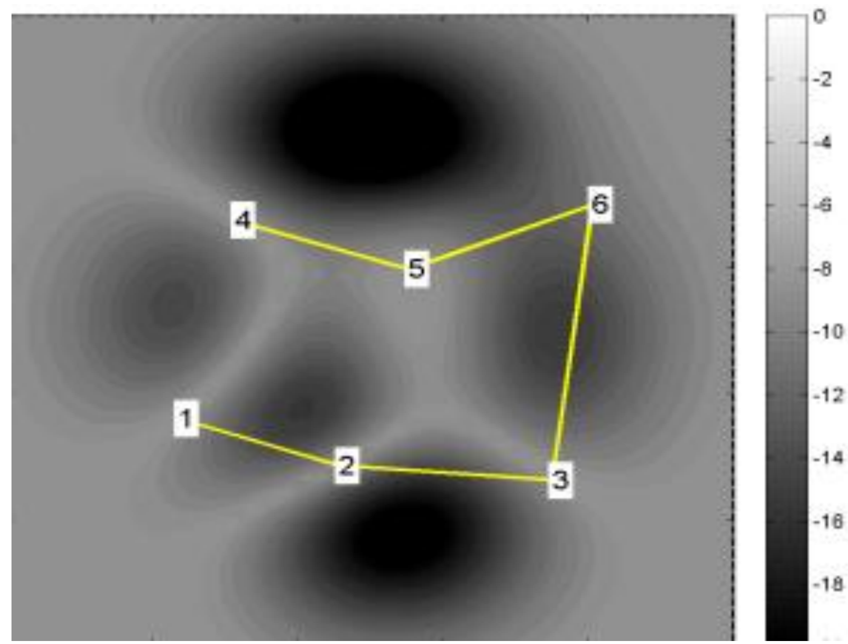


Gray color: Water depth [m]
Yellow line: Electrical grid

TOPFARM – example applications (2)

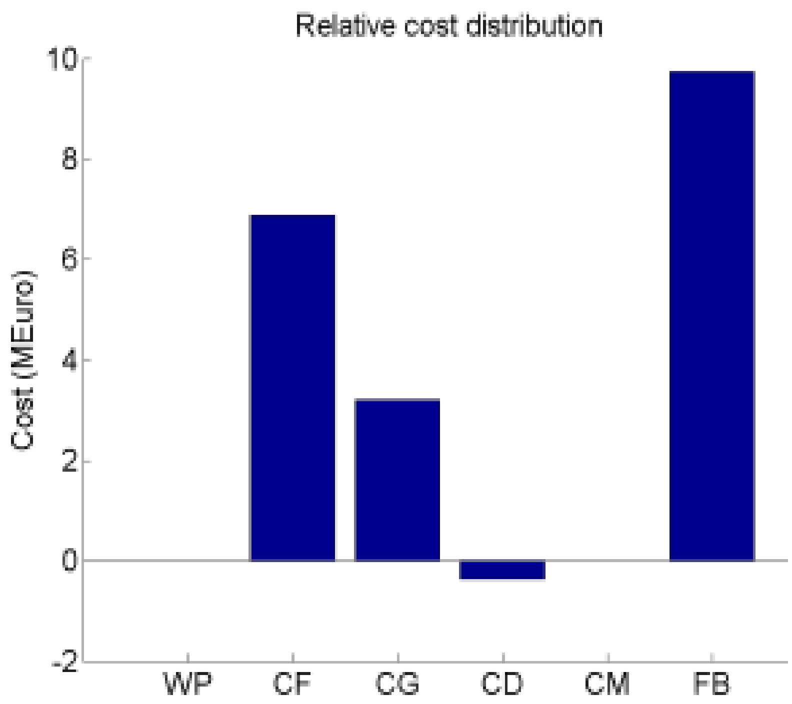
- Result of a gradient based optimization (SLP) ... relative to base line:

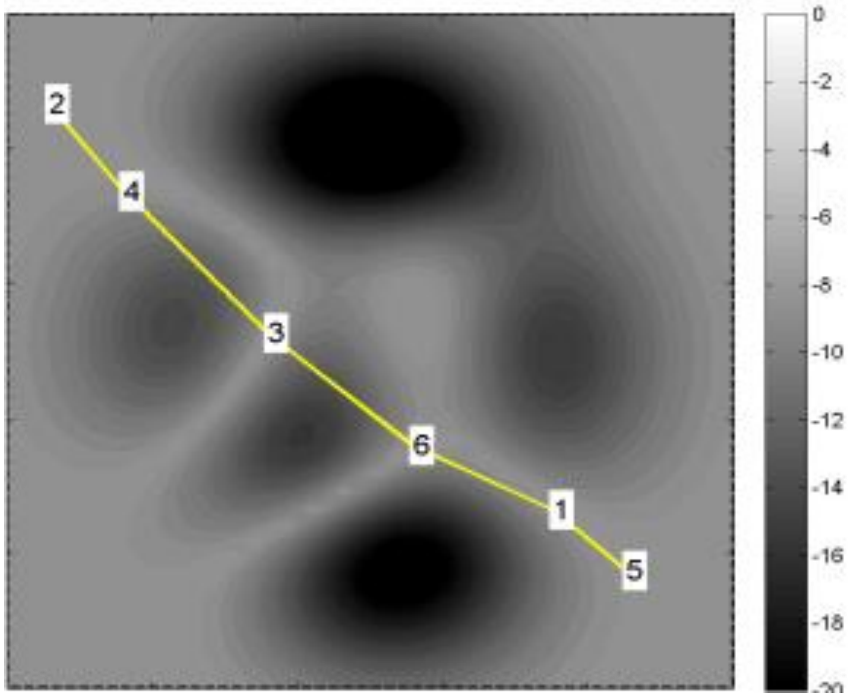




TOPFARM – example applications (3)

- Result of a genetic algorithm + gradient based optimization (Simplex) ... relative to base line:



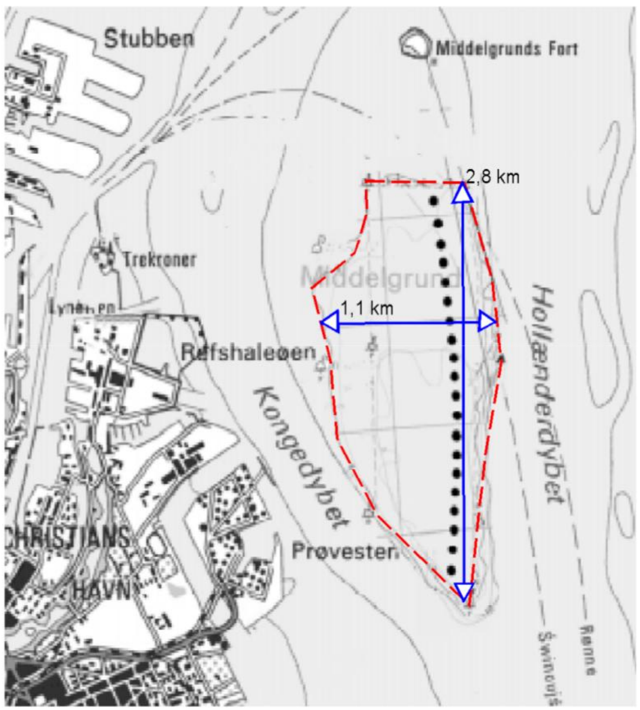


TOPFARM – example applications (4)

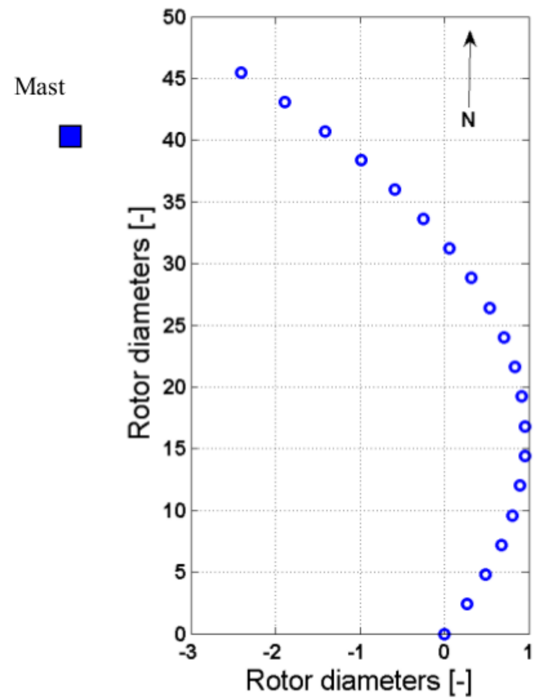
- Middelgrunden

TOPFARM – example applications (5)

- Middelgrunden



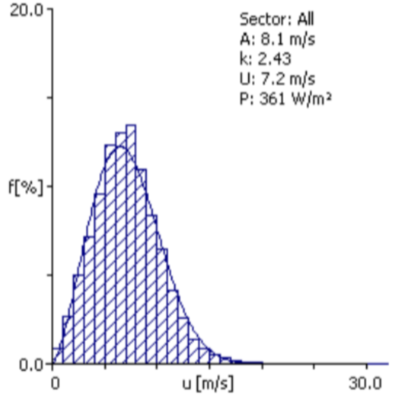
Allowed wind turbine region

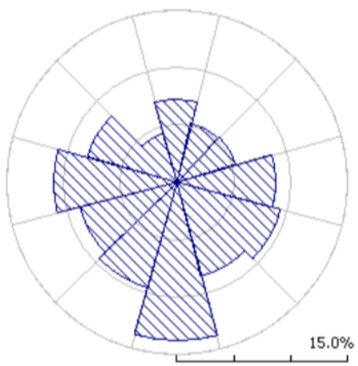


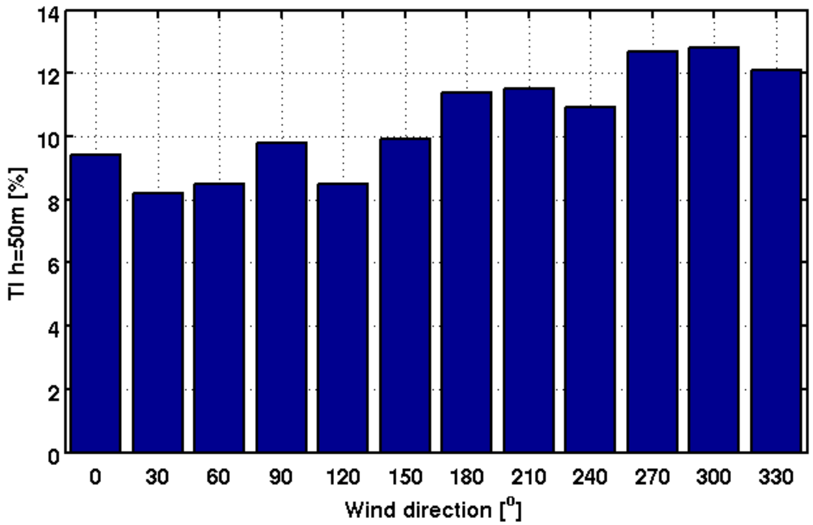
Middelgrunden layout

TOPFARM – example applications (6)

- Middelgrunden - ambient wind climate

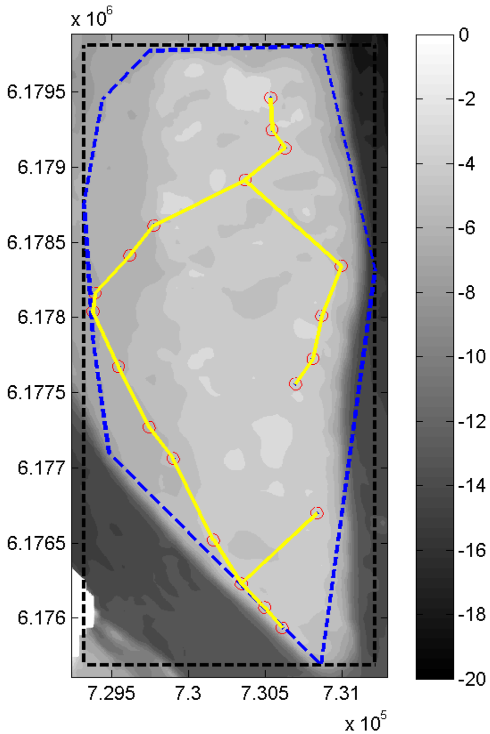


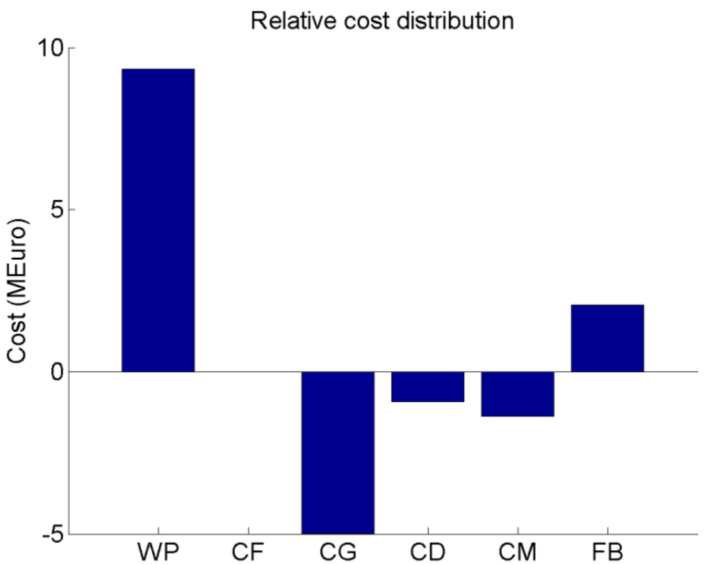




TOPFARM – example applications (7)

- Middelgrunden iterations: 1000 SGA + 20 SLP

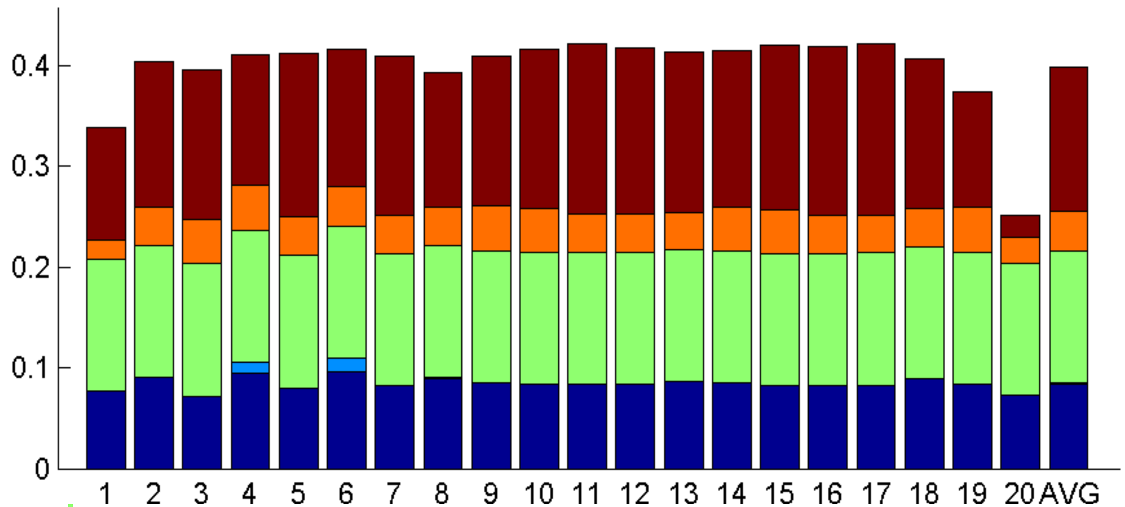


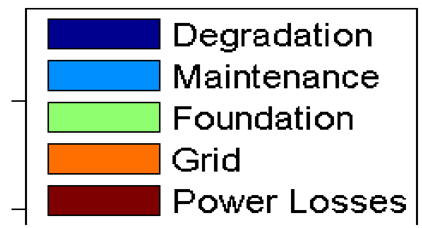


Optimum wind farm layout (left) and financial balance cost distribution relative to baseline design (right).

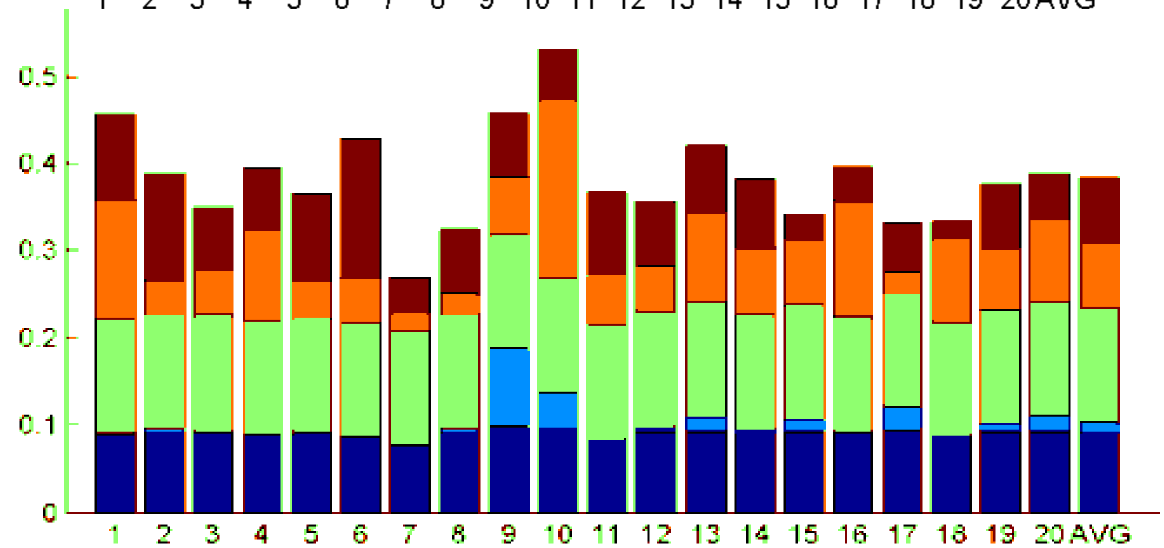
TOPFARM – example applications (8)

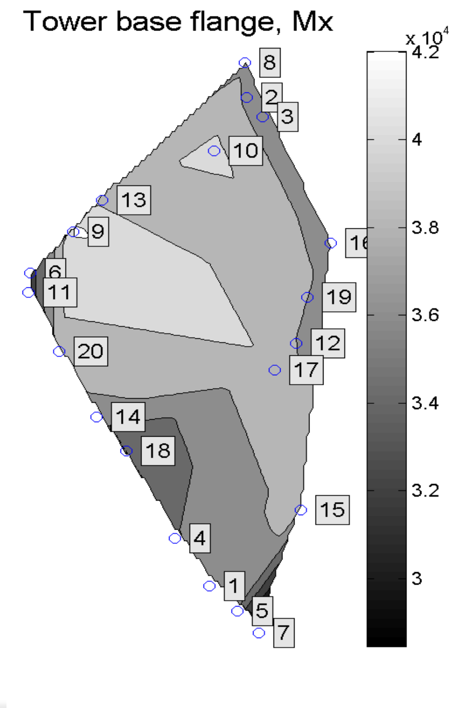
Before





After





TOPFARM – example applications (9)

- Evaluation:
  - The baseline layout was largely based on visual considerations
  - The optimized solution is fundamentally different from the baseline layout ... the resulting layout makes use of the entire feasible domain, and the turbines are not placed in a regular pattern
  - The foundation costs have not been increased, because the turbines have been placed at shallow water
  - The major changes involve energy production and electrical grid costs ... both were increased
  - A total improvement of the financial balance of 2.1 M€ was achieved compared to the baseline layout ... over the WF lifetime

TOPFARM - Future activities

- More detailed and realistic cost functions
- Improvement of the code (e.g. parallelization)
- Inclusion of WF control in the optimization problem
- Inclusion of atmospheric stability effects in the WF field simulation ... basically by developing a spectral tensor including buoyancy effects
- Cheapest rather than shortest cabling between turbines
- Inclusion of extreme load aspects
- Simplified aeroelastic computations in the frequency domain … to improved computational speed
- Development of a dedicated “self-generated” wake turbulence spectral tensor
- Development of a more DWM-consistent eddy viscosity

References (1)

- Larsen et al. (2011). **TOPFARM -** NEXT GENERATION DESIGN TOOL FOR OPTIMISATION OF WIND FARM TOPOLOGY AND OPERATION. Publishable final activity report. Risø-R-1805 (EN)
- Rethore, P.-E.; Fuglsang, P.; Larsen, G.C.; Buhl, T.; Larsen, T.J. and Madsen, H.Aa. (2011). TOPFARM: Multi-fidelity Optimization of Offshore Wind Farm. The 21st International Offshore (Ocean) and Polar Engineering Conference, ISOPE-2011, Maui, Hawaii, June 19-24
- Larsen, G.C.; Madsen, H.Aa.; Larsen, T.J.; Rethore, P.-E. and Fuglsang, P. (2011). TOPFARM – a platform for wind farm topology optimization. Wake Conference, Visby, Sweden, June 8-9

References (2)

- Buhl T. and Larsen G.C. (2010). Wind farm topology optimization including costs associated with structural loading. *The Science of Making Torque from the Wind, 3rd Conference, Iraklion, Greece*
- Larsen, G.C. (2009). A simple generic wind farm cost model tailored for wind farm optimization. Risø-R-1710(EN)
- Larsen, G.C. (2009). A simple stationary semi-analytical wake model. Risø-R-1713(EN)
- Larsen, G.C. et al. (2008). Wake meandering: A pragmatic approach. *Wind Energy*, **11**, 377-395

ABL stability effects

- Analyses of full-scale measurements from Danish (offshore) wind farms wind farms have shown a significant dependence of wake losses on atm. stability conditions [e.g. L. Jensen; EWEC 2007]
- Horns Rev; 8m/s; 90 deg.; un-stable ctr. stable